Exhibit G

TECHNOLOGY REVIEW

Sourceless Trackers

Robin Hollands

Much of the most advanced technology for 'sourceless' trackers has been developed for use in inertial guidance systems for missiles and other military hardware, and is unlikely to be commercially available in the near future. The VR marketplace, which could consume in the future very large numbers of low-cost, high-performance sourceless trackers, will just have to rely on commercial and academic R&D. In this article, Robin Hollands provides a status report, a beginner's guide to some of the technologies of sourceless trackers, and a list of useful contacts.

Most forms of tracker system used in virtual reality applications introduce restrictions because of the need for a source. Whether the technology used is mechanical, ultrasonic or electromagnetic, all require some form of base station from which to assess position and orientation. This requirement leads to a number of possible problems: operating range limitations, line-of-sight obstruction, etc. Sourceless trackers on the other hand are by definition tracking systems that do not require a base, or source, and these problems do not therefore arise. In theory, a sourceless tracker could operate in any environment and over an unlimited operating range, surely making it the ideal solution for almost any VR application.

However, despite the obvious desirability of such a device, a survey of the field reveals a surprising lack of research activity, either commercial or academic.

The only full time researcher found was Eric Foxlin, at MIT, and I am indebted to him for much of the information in this article.

For full six degrees of freedom tracking, both orientation and linear position need to be determined. There are a number of technologies and methods that can be used to assess either or both of these, of which the following will be considered in this review: – inclinometer, compass, gyroscope, accelerometer, and optical flow.
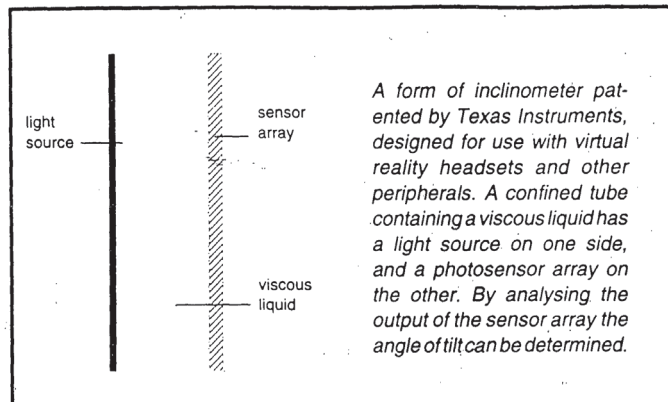
Inclinometers

Inclinometers, or tilt sensors, measure the tilt of an object with respect to gravity. Although this makes them not truly sourceless (since the mass of the earth is their source), operating range is effectively infinite and interference negligible. In essence, an inclinometer is purely

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VR NEWS

A form of inclinometer patented by Texas Instruments, designed for use with virtual reality headsets and other peripherals. A confined tube containing a viscous liquid has a light source on one side, and a photosensor array on the other. By analysing the output of the sensor array the angle of tilt can be determined.

an instrumented pendulum. A simple inclinometer can be homebrewed by hanging a weight from two perpendicular potentiometers. Commercial 2-axis inclinometers consist of a small glass bubble, half-filled with an electrolytic fluid, and containing five electrodes. As the sensor is tilted, the level of the fluid on each electrode changes, which can be sensed by the driving electronics and converted into pitch and roll values.

Although it is typically used for measuring tilt with respect to gravity, it should be noted that what the inclinometer is actually measuring is the direction of total acceleration. If the sensor is stationary with respect to the room, then all of the acceleration is caused by gravity and the tilt sensor gives a correct reading. However, if the tilt sensor is attached to a moving head, the inclinometer will also be affected by the accel-

eration of the head moving around, resulting in an incorrect reading of tilt. This combined with the settling time of the fluid within the sensor can lead to the virtual world 'sloshing around' for rapid movements. Electrolytic inclinometers also have a finite rotational operating range, determined by the angle at which the electrodes become dry.

Tilt switches

It should be noted that tilt sensors are different from tilt switches. Tilt sensors provide an analogue measure of tilt over their operating range. Tilt switches typically consist of a small quantity of mercury in a miniature container with two contacts in its base. When the tilt switch is upright, the mercury closes the circuit between the two contacts. When the switch is tilted, the mercury rolls off the contacts opening the circuit. Tilt switches

can detect only whether the tilt angle is greater or less than their activation angle, but not what the value of the tilt is. Multiple tilt switches, each at a slightly different angle, can be multiplexed to provide a pseudo-continuous reading of angle, but are usually incorporated into low-cost flying joysticks to provide simple left/right back/forward controls.

Although inclinometers can be very good at providing a reading of any rotation relative to the vertical, rotations in a horizontal plane, or heading, will not affect a pendulum device and require a different sensing technology. Luckily nature provided a second 'source' for sourceless trackers to use - the earth's magnetic field.

Compasses

The earth is effectively a giant bar magnet with the magnetic north pole near the physical north pole and a magnetic field running from north to south. Although this rarely runs parallel with the surface of the earth, in most places it has a horizontal component that can be sensed for heading purposes. Simple compasses contain a low friction surface supporting a magnetised bar which aligns itself with the local magnetic field.

Hall effect semiconductors

Although these have been used via servos to electronically measure heading, most miniature electronic compasses now use

GRAVIMETRIC TRACKERS	Accuracy		Resolution		Repeatability		Range		Update
	Heading	Tilt	Heading	Tilt	Heading	Tilt	Heading	Tilt	Rate
General Reality									
CyberTrak	±0.5°	±0.2°	0.1°	0.2°	±0.1°	0.2°	360°	±25°	8Hz
VictorMaxx Technologies									
Cybermaxx tracker	±5°-±3°	±1°	±0.1°	±0.1°	0.1°	0.1°	360°	±45°	30Hz-8Hz

Hall effect semiconductors. Hall effect compasses use Fleming's left hand rule. In motors, a current flowing in a magnetic field results in a motion in a plane perpendicular to the two, spinning the rotor. If the current is flowing through a semiconductor device in a magnetic field, the resulting motion takes the form of the electrons moving to one side. This results in a higher concentration of electrons on one side of the semiconductor than the other, which can be measured as an e.m.f. across the slice.

When used as a compass, an individual hall effect sensor will report the component of the earth's magnetic field aligned with it. This can lead to ambiguities between say, NE and NW, and therefore another perpendicular Hall effect sensor is used. The two readings can be combined using trigonometry to find the local magnetic north.

Calibration

Electronic compasses suffer from two main problems. The first is that the dip and direction of the earth's magnetic field varies according to location, resulting in a need to calibrate the unit in its local area. The second problem is analogous to that which affects electromagnetic trackers, namely that the earth's magnetic field is subject to interference from ferrous metal in the environment, e.g. furniture, wall reinforcements, head mounted displays etc. Researcher Eric Foxlin has found that this can cause variations in magnetic north

of ± 30 degrees within a few feet.

Gravimetric sensors

Electronic compasses are usually combined with an inclinometer (producing what is sometimes referred to as a 'gravimetric' sensor) to provide a full 3DOF orientation system, the quality of which can vary – see comparison table at foot of page opposite.

Gyroscopes

The most common type of gyroscope is the spinning wheel type, similar to those found in toy shops. A relatively heavy wheel is spun freely suspended in a supporting frame. The spinning mass has a large rotational inertia resisting rotation away from its plane. This has the effect that the gyroscope continues to point in the same direction, regardless of the orientation or movement of the base the frame is mounted on. Instrumenting the gimbals on the supporting frame can therefore provide a two degree of freedom indication of orientation. Another gyroscope oriented perpendicularly to the first is required to give a full three degree of freedom orientation measurement.

Because gyroscopes rely purely on inertia, they are genuinely sourceless, and will even work in space, dependant neither on gravity nor any magnetic field. This does however give rise to a problem. Simplistically, a gyroscopic pointed at the sun will stay pointed at the sun,

regardless of the motion and rotation of the earth. This leads to apparent rotation and dipping of the orientation of the gyroscope when viewed on the earth.

For this reason a normal gyroscope is not appropriate for use as a compass; however the addition of a weight on the inner gimbal ring on the gyroscope assembly results in eccentricity in its motion. This causes the gyro gradually to align itself with the third 'source' that nature has put in place for sourceless trackers – the rotation of the earth. This in turn causes the axis of the gyroscope to swing round until it points north, and this can provide a much more accurate compass than any magnetic system.

Rate gyroscopes

Gyroscopes only continue pointing in the same direction in a theoretically ideal system. In the real world it is hard to achieve frictionless gimbals in the gyroscope assembly, and any friction causes a drift in the readings. Many gyroscopes are not of the position variety, reporting the absolute angle of the gyroscope wheel, but of the rate gyroscope variety, reporting the rate of change of the gyroscope angles. To get position information from these, the rate must be integrated. Any error in the rate readings will cause an extra term in the integration, which reveals itself as further drift. This is typically in the order of 1 degree per minute, i.e. if the user stands perfectly still, the virtual world will rotate 60 degrees in an hour.

GYROSCOPIC TRACKERS	Accuracy		Resolution		Range		Update Rate
	Yaw	Pitch & Roll	Yaw	Pitch & Roll	Yaw	Pitch & Roll	
VR Systems UK GyroTRAC	15°/min drift (max)		0.003° — 0.032°		±6° — ±66°		50Hz
Angularis Inertial Tech. Prototype	~3°/min drift	1°	0.0082°	0.0082°	±180°	±90°	1KHz

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Although this rate of drift would not be immediately noticeable in an opaque head mounted display, the cumulative effect in tilt or roll will eventually become obvious and must be compensated for in a useable system, usually by measuring the drift on a stationary object for an extended period of time, and then using this as a compensating factor. The problems mentioned before with the earth's rotation can be compensated for similarly.

Gyroscopic trackers used for manipulation purposes often have a clutch button that only reads data from the tracker when a movement is desired to be recorded. Because all movements are therefore relative, drift is not a significant problem.

Coriolis effect

Rate gyros also come in solid state form, and use the Coriolis effect, named after the French engineer and mathematician who first drew attention to it (and who also wrote a treatise on the mathematics of the game of billiards). The Coriolis force is experienced by anything moving on a rotating body, and is exerted perpendicular to both the axis of rotation and the direction of the velocity. A simple experiment is to stand on the outside of a child's merry-go-round facing the centre while it is spinning, and then try to kick the axis; the Coriolis force will cause your foot to go to one side.

The same principle is used in Murata's piezoelectric gyroscope which consists of a triangular prism, with an exciter on one face and receivers on the other two. The exciter sends out pulses (kicks) at the prism's resonant frequency, which are picked up equally by both detectors. Any rotation around the axis of the prism produces a Coriolis force, which causes the amplitude of the received signal to be greater at one detector than the other. The rate of rotation can then

be measured as a proportion of the difference between the two detector readings.

Systron-Donner's rotation sensor operates in a similar way with a piezoelectric tuning fork type device whose prongs oscillate in a single plane. The application of a rotation causes a Coriolis force making the prongs also oscillate in a perpendicular plane with an amplitude proportional to the rate of rotation.

It appears that the only gyroscopic headtracker available off the shelf is that offered by VR Systems UK, although Willow Technologies have announced the prototype of a rate reporting gyroscopic tracker, and Eric Foxlin's start-up company Angularis Intertial Technologies also has an orientation tracker in the prototype stage.

Although gyroscopes or inclinometer/compass trackers can measure orientation well, both have the disadvantage of

not being able to measure location in space. One possible solution to this is to use accelerometers.

Accelerometers

Accelerometers are simply devices that measure acceleration in a given direction. Most use Newton's second law, i.e. Force=mass*acceleration. This is often measured by a mass attached to piezoelectric material. Any acceleration causes the mass to exert a force on the piezoelectric material which generates an e.m.f. in response. Accelerometers can also be based around spring masses moving along a linear potentiometer, or in a capacitor or inductor.

To get position data from the acceleration data is simply a matter of integrating the result twice. However, in the same way as a single integration caused rate gyroscope errors to appear as drift, the double integration causes any accelerometer errors to grow quadratically

Piezoelectric Accelerometer

Piezoelectric material

Seismic Mass

Direction of Motion
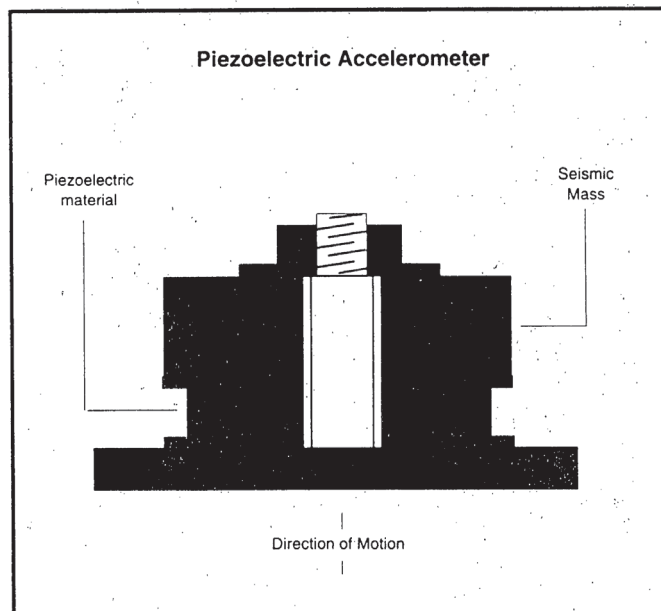
with time. There is also a problem with gravity, which is also an acceleration. A stationary accelerometer pointing straight down will read an acceleration of 9.81ms-2, and any accelerometer not exactly perpendicular to gravity will always exhibit some component. Remember that any errors measuring the real acceleration show as quadratically increasing errors when integrated to position! It is for this reason that accelerometers cannot be used in isolation, but must be used with an accurate inclinometer.

Although miniature low-cost accelerometers are available, these have been developed for the automotive industry for use in crash bags and measure accelerations of around 50g. Typical human head accelerations rarely exceed 2g and are usually out of the usuable range of these devices.

Because of all the problems involved with accelerometers, it is perhaps no surprise that no companies were found that have a successful accelerometer-based position tracker, although one is under development by Angularis Inertial Techologies

Optical flow

Apparently still only a theoretical system at present, optical flow uses a set of cameras mounted on the tracker to process the optical flow of an unstructured environment around it. In simple terms, this involves using real-time image processing to extract features from the environment, measuring apparent position changes of the features as the user moves around, and continuously computing the user's position relative to the features.

For more information see Bishops G. and Fuchs H., "A self-tracker: a smart optical sensor on silicon" in Proc. 1984 Conference on Advanced Research on VLSI.

Conclusions

There are undoubtedly problems and deficiencies with currently available sourceless tracking systems and technologies. Although these may eventually become insignificant over time with the development of better sensors, the answer may well lie in hybrids of different sourceless technologies, used perhaps in combination with sourced tracking. For example, compass/inclinometer systems can produce very accurate results for a stationary body, gyroscopes are accurate for a short time but suffer from drift.

A possible solution being developed by Angularis Intertial Technologies is to use the compass/inclinometer system to automatically recalibrate the gyroscopic system in 'quiet' moments. In a similar fashion, ultrasonic trackers could be used to recalibrate the much faster but error-prone accelerometer based position trackers. Even global technologies such as the satellite GPS (Global Positioning System) could be called upon for large scale systems.

Sourceless trackers, used in combination with wireless signal transmission and portable workstations and battery packs, offer the prospect of virtual world navigation free from the shackles of a base station. Although the desirability of a HMD-blinded user stumbling around without restraint may be questioned, free ranging use will certainly be necessary for many of the augmented reality applications to come. Exponents of sourceless tracking also point out,that the removal of a requirement for signal transmission and reception, and the specialised signal processing hardware found in many sourced trackers, should produce exceptionally cheap units. Truly sourceless technologies, such as inertial systems, are also immune from the interference that plagues current users of electromagnetic and ultrasonic tracking systems. In the end, it may well purely

be the convenience of sourceless tracking that makes it the system of the future.

Contact List

The list which follows on pages 28 and 29 has been divided into two colour-coded sections. The first section comprises organisations who manufacture, or are planning to manufacture sourceless tracking systems. In this context a system is defined as a sensing unit that is ready for computer connection, i.e. plug-and-play. The second section lists a selection of vendors of sensor components, for the benefit of organisations and researchers thinking of developing a sensor system. Note that the basic sensors used in sourceless devices are also found in numerous other applications. The list of sensor suppliers is limited to vendors known to provide sensors for existing VR systems, or whose existence has been brought to our attention by those working in the field.

***Robin Hollands** is Research Associate at the University of Sheffield, founder and Chairman of the United Kingdom Virtual Reality Special Interest Group, and Fellow of the Virtual Reality Society. For his Ph.D. he researched the use of virtual reality in industrial process simulation, built a fully immersive VR system from scratch for less than £1000, and wrote simulation and rendering software to support it. He is presently developing an arthroscopic surgical simulator, and writes for VR magazines and journals on all aspects of the VR field.*